Amendment to NRA 02-OBPR-03

RESEARCH OPPORTUNITIES IN PHYSICAL SCIENCES

APPENDIX E: MATERIALS SCIENCE

It was indicated in the original release of NRA 02-OBPR-03 that an amendment to Appendix E would be issued approximately three months before the proposals are due. The following comprises that amendment. It includes further detailed information concerning In-Space Fabrication and Repair for Exploration (section III), and Materials Science for Advanced Space Propulsion (section IV). The new information resulted from workshops held May 15-16, 2003 (Advanced Space Propulsion Materials) and July 8-10, 2003 (In-Space Fabrication and Repair). Workshop agendas and presentation materials are available at http://msad.msfc.nasa.gov/workshops/.

Points of contact for further technical information:

Materials Science for Advanced Space Propulsion:

Douglas L. Blackwell
Deputy Manager for In-Space Propulsion Technology Projects Office
Mail Code TD05,
George C. Marshall Space Flight Center
MSFC, AL 35812
Phone (256) 544-2255
Douglas.L.Blackwell@nasa.gov

Dr. Donald C. Gillies (radiators only)
Materials Science Discipline Scientist
Mail Code SD41
George C. Marshall Space Flight Center
MSFC, AL 35812
Phone (256) 544-9302
Donald.C.Gillies@nasa.gov

In-Space Fabrication and Repair for Exploration:

Dr. Neville I. Marzwell
Jet Propulsion Laboratory
4800 Oak Grove Drive
M/S: 180-603
Pasadena, CA 91109-8099
Phone (818) 354-6543
Neville.I.Marzwell@jpl.nasa.gov

III. IN-SPACE FABRICATION AND REPAIR FOR EXPLORATION

INTRODUCTION

Future NASA missions and exploration capabilities will demand materials development to live off of the planets. This requires innovative in-space fabrication and repair methods based on in-space resources with as little as possible brought from Earth. The development of these methods is a natural extension of the microgravity materials science research program of the Physical Sciences Research Division in the Office of Biological and Physical Research (OBPR). It initially addresses the immediate needs and engineering requirements of the space program, then understanding of the behavior of various materials in a space environment, and eventually the actual processing of materials in space. Such activity will not only allow (and require) a greater understanding of the role of gravity in some of these processes, but will also enable new materials to be synthesized. The scientific understanding of the relationships between the structure, processing, and properties of materials and the new experimental and computational methods developed by the program will lay the foundation for identifying the potential and limitations of in-space fabrication and repair and the utilization of in-space resources for NASA's exploration program in the next decade.

The materials found on the Moon, Mars, its moons, and near Earth asteroids provide most of the elemental basis for in-space fabrication of crucial items needed for exploration. Space resource development is essential because the high cost of transporting materials can be ameliorated if much of the material can be produced in space. A better understanding of the processes and technology needed to enable the acquisition of materials/feedstocks resources available *in situ* and the attendant materials handling requirements is part of the broader perspective of in-space fabrication. Markets for space resources do not currently exist. However, it is clear that space resource development is crucial to the human exploration and development of space. If humans are ever to spend long times in a remote space environment, they will be sustained by space resources, not supplies brought from Earth.

OBPR seeks to advance the basic research needed for the identification, development, and validation of highly innovative technologies and systems concepts that will open up new options for exploration and commercial development of space based on "living off the land." This research will pursue specific basic research and technology development not otherwise addressed by NASA's various Research & Technology programs, and will result in a better understanding of the materials science strategic technical challenges that must be solved if fabricating components and repairing elements and structures in space is to become a reality. Materials selection issues may include the identification and development of materials best suited for the harsh environment of space. The goal is to acquire, refine, and produce materials in space for use in that environment to enable, facilitate, and support all needed capabilities for exploration. Aspects of the work involve the fabrication and repair of components and structures either contained within a spacecraft, on a celestial body, or free-floating in the space environment. This portion of the NRA supports a broad scope of efforts, including basic, theoretical, and applied research as well as technology development.

Types of activities solicited by this research opportunity include the categories defined below. It is anticipated that grants of the order of $150K to $200K per year for basic research and technology development will be awarded. Smaller, innovative, high-risk, high-payoff studies are desired, and very limited number of larger grants seeking to provide the development of unique capability leading to flight demonstrations will be considered. Anyone planning to submit a proposal in the materials science research topic of this NRA should check the following Web site for updated information: http://spaceresearch.nasa.gov

Physics, Chemistry, and Characteristics of Materials under Microgravity

The utilization of space resources is critical to moving towards self-sufficiency by living off the planets for the safe and sustainable support of personnel and equipment beyond earth orbit. If an integrated robotic and human approach to space science and exploration is to become viable in the next decade, it is essential to develop the capability to extract, process, and transform (under microgravity conditions) the essential materials beyond Earth orbit. This program provides the essential science and technology base to support these mission designs.

Except in a very limited number of cases, materials behavior during processing under microgravity conditions is not well understood, yet is critical to in-space fabrication and repair for life support, energy, and propellant production. Special emphasis needs to be placed on the chemistry and physics of extractive processes for the key materials such as silicon, metals, oxygen, and water. These processes are, although not fully determined, dependent heavily on and impacted significantly by the effects of microgravity.

Subtopics critical to this research and supported in the Fluid Physics Discipline of the Physical Sciences Research Division are the understanding of the physical/chemical properties of *in situ* soils on planetary bodies and flow and dynamics of *in situ* granular media (complex fluids). Also critical is the understanding of multi-phase fluid reactions in chemical reactors.

It is also critical that soil analogs of these planetary surfaces be developed to serve as standard source materials for the various extractive processes proposed. It is therefore essential to develop the theory and validate the understanding of the underlying basic physical phenomenon to enable the design of efficient reactors for reduced gravity conditions. The development of basic scientific understanding needed to support concepts and technologies for site preparation and soil beneficiation is critical to enable *in situ* energy and propellant production and life support. These extracted materials and processes will eventually enable cost effective future development of sensors, instruments, and very large space science facilities in space using *in situ* resources. These resources will also serve as additives to earth provided materials for in space fabrication and repair.

Instruments, sensors, equipment, and facilities are also needed to understand, monitor, and evaluate materials behavior, and to enable the processing and controls for extraction, refining, purification, storage, fabrication, and repair. These facilities and supportive infrastructures are supposed to be designed for and functional in reduced gravity conditions. Projects providing NASA with critical strategic research will be able to access reduced gravity using the KC-135 aircraft, or perform flight experiments on the Space Shuttle or the International Space Station. Strategic Research includes basic and applied research for which NASA relies uniquely upon OBPR in order to conduct and enable NASA's mission to explore the universe and search for life. Any research selected as a flight experiment will be conducted in a highly focused fashion with guidance from OBPR and subject to NASA and external review processes.

PROGRAM RATIONALE

In-Space Fabrication and Repairs are needed to support NASA's exploration objectives.

The realization of NASA's objectives in the exploration of the Solar System and interstellar space will require the transition from an Earth-dependent program to a self-sustaining space-based program aimed at discovering and extending life in space. The key leveraging element to accomplish this is the ability to acquire and process mass from outside of the deepest part of Earth's gravity well. This presents some unique and formidable challenges. However, the development of the technology required to exploit extraterrestrial resources in reduced-gravity environments, where the greatest leveraging exists, will ultimately enable the expansion of human presence in space. The ability to maintain a continuous presence in deep space will enhance safety and reduce operational costs by the use of mature technologies capable of transforming space resources into manufactured parts and space hardware beyond Earth's surface. In-space fabrication and repair comprises a major strategy shift that requires innovative approaches based on our improved understanding of the gravitationally dependent elements of materials processing. This understanding is needed to ensure the timely development of new technologies that enable the construction of spacecraft and other structures that cannot be launched due to cost, size, or structural constraints.

Indeed, materials processing stations distributed throughout the solar system will enable locally supported resupply and thus extend our ability to explore the far reaches of space. The successful exploration of extraterrestrial regions requires the ability to process mass obtained from outside the influence of Earth's gravity. Site preparation, mining, materials processing, habitat construction, and infrastructure development must evolve rapidly away from dependence on terrestrial systems that have been transported from Earth in order for in-space fabrication to realize its full potential.

The ability to maintain a continuous presence in deep space will enhance safety and reduce operational costs by the use of mature technologies capable of transforming space resources into manufactured parts and space hardware beyond Earth's surface. In-space fabrication and repair comprise a necessary group of technologies that enable the manufacture of components and structures that cannot be launched due to cost, size, time, or structural constraints.

Materials Science research is needed to support the required technological advancements.

NASA's future exploration efforts will demand the use of mature technologies to manufacture parts and space hardware in the space environment. The construction and fortitude of large space structures in deep space (orbital or planet bound) will depend on our ability to fabricate and repair complex parts from available in-space resources. The purpose of the present effort is to create better understanding through basic research, theoretical modeling, and experimental work regarding materials behavior under reduced gravity conditions. The research sought is to cover all aspects of materials changes during all processes (refinement, purification, transformation, melting, and solidification) involved in the repair and fabrication functions. An issue that needs to be addressed is the control of melt pools in microgravity and an understanding of how it is different from Earth. The coupling between microsegregation during solidification, heat transfer, and microstructure formation is another basic issue that needs to be better understood. To develop a better understanding, new tools, equipment, instrumentation, and materials conversion and refinement facilities may be needed.

We seek to develop the specific understanding, expertise, and technology to handle the challenges involved in the evolution of an Earth-dependent exploration program to an autonomous, space-based program.

RESEARCH AREAS OF INTEREST

Research in this new theme supports the basic and applied research and technology development needed to develop methods for in-space fabrication. Fabrication encompasses a variety of materials processing technologies, which include casting, sintering, and welding as well as emerging materials forming technologies that are envisioned for a range of settings. These settings include the microgravity environment experienced on board spacecraft, on the International Space Station, and on the satellites of Mars, or the fractional gravity environment that would be encountered on the Moon (~0.169g) or Mars (~0.38g). Some of the identified needs of NASA’s exploration Enterprises include fuel, water, materials, and power. The research should be directed towards providing innovative, efficient, and compact solutions to the challenges faced in processing materials in the unique environment of space.

In-Space Materials Fabrication

Fabrication of components during space missions will be one of the key elements for developing a self sufficient space exploration capabilities. Specifically, this will reduce reliance on spare parts supplied from Earth and will enable production of components and deployable structures that cannot be launched from Earth, either because they are cost or size prohibitive or because they cannot withstand launch loads. These “free space” operations present a unique set of technical challenges created by the space environment. High vacuum, intense radiation of many types, large temperature gradients, high momentum objects, and levels of gravity ranging from microgravity to extraterrestrial surfaces to localized artificial gravity characterize this environment. The need to process materials under such extreme conditions demands a thorough study of the behavior and properties of materials that will enable imaginative solutions and the development of robust technologies. Research, as specified by NASA’s Exploration Team (NEXT), is needed in these critical areas of advanced materials and in-space fabrication processes: habitat and deployable structures, thermal protection systems, electronic and photonic materials, and dual- or multi-purpose materials. Process simulation and predictive modeling will be beneficial for designing advanced materials and fabrication processes in a cost effective manner.

In addition to feedstock brought from Earth, studies should consider materials that are expected to be available in space, such as salvaged spacecraft parts, or materials that can be derived from processing of lunar, planetary, or asteroid materials. The processing of local resources to obtain various materials will be crucial to space exploration. This *in situ* resource utilization (ISRU) would include the beneficiation of local regolith and the extraction of essential materials.

The surface environments associated with resource-rich extraterrestrial bodies offer many challenges. In addition to the fractional gravity environments of the Moon and Mars, both have widely varying local surface temperatures and surface pressures ranging from a hard vacuum on the Moon to (approximately) water's triple-point pressure at Mars. Their surfaces have relatively severe dust problems, associated on the Moon with the abrasive character of very fine lunar dust and on Mars with the planet-wide dust storms that are observed with some regularity. This is mentioned because a better understanding of the behavior of extraterrestrial soil in reduced gravity environments will be needed before surface operations can be carried out to acquire, transport, and handle *in situ* resources for in-space fabrication.

"Free space" fabrication processes will be involved in the manufacture of a variety of objects of different geometries: surfaces (e.g., solar sails and panels, solar collectors, radiators, shields), structural elements (e.g., trusses, beams, shells), ribbons and fibers (e.g., electrical and optical circuitry, antennas) and small complex parts (e.g., fasteners, mechanical devices). To achieve these goals, research is needed on the behavior of materials throughout the entire process, from handling raw materials to incorporating them into finished parts, under the unique conditions defined by the space environment. There will be a need to refine metals from local ores as well as performing the manufacturing operations. Specific areas for research are described below.

Casting: The procedure of casting wherein a molten material is allowed to freeze or solidify to produce a solid object of the desired shape also merits investigation. Molds could be of the sand or lost wax technique or made of *in situ* resources. Alternatively, containerless solidification is considered when contamination from a container would prevent obtainment of desired properties.

There is an extensive body of knowledge on casting in terrestrial gravity. Furthermore, a significant amount of work has also been done on microstructural evolution during controlled directional solidification on both metals and semiconductors in microgravity. However, there is insufficient understanding of the effect of gravity on microstructural evolution in a casting during multidirectional solidification.

In general, the solidification process and the resulting microstructure are affected by gravity. The effect is ultimately due to differences in the strength of density-induced convection in the liquid phase. These differences affect the distribution of temperature, solute, and suspended particles or bubbles, which in turn affect the solidified microstructure. Moreover, casting operations may perform differently in reduced gravity. For example, many casting operations depend on the gravity feed of liquid by way of risers as part of the design of the mold. At reduced gravity, such feeds would be less effective and would be totally ineffective under microgravity conditions, where forced melt infiltration would be needed.

Sintering: Sintering is an important manufacturing process for making near-net-shape items from powders in the solid state when heated to temperatures in excess of approximately half the absolute melting temperature. Sintering offers advantages over casting, including its capability to (1) use high-melting-point materials, (2) produce porous materials as used in self-lubricating bearings, and (3) use mixed powders, whose separate liquids are immiscible, to produce materials that can't be formed by casting.

Liquid phase sintering (LPS) is a subclass of the sintering process involving particulate solid along with a coexisting liquid during some part of the thermal cycle. This liquid presence is advantageous in that it provides both a capillary force and transport medium that leads to rapid consolidation and densification.

The diffusive transport processes that occur during solid-state sintering are not affected to any significant degree by the level of gravity. The spatial distribution of particles, however, is affected by it. In microgravity, an aggregate of independent particles would not form a compact unless pressure were applied, with the effective coordination number dependent upon the pressure.

Similarly, the distribution of particles in LPS is affected by gravity level. Gravity induces separation of the liquid phases due to density differences between the two. Consequently, the microstructure would evolve differently in gravity than the way it would in its absence. This difference in microstructure affects the sintering kinetics and thus affects the materials properties. If the volume fraction of particles is low for LPS under microgravity, the particles tend to agglomerate toward the center, surrounded by liquid. This agglomeration may be driven by the reduction of surface and interfacial energy that can occur when particles coalesce to form grain boundaries at their junctions.

Thus microgravity LPS investigations could help understand the problems of pore formation and metamorphosis, the effect of capillary forces, and the effect of Brownian motion.

Joining: Joining of materials in space is needed for both construction and repair. Typical joining methods are mechanical, adhesive bonding, and welding or soldering (including brazing).

Unfortunately, the polymers used for adhesive bonding are subject to degradation in space due to out-gassing and radiation damage. Thus a materials development need exists for a suitable adhesive that can withstand the rigors of the space environment.

While there have been successful welding experiments conducted is space under both the Russian and American space programs, further research is needed.

Gravity is not a dominant factor in the welding process itself. Under microgravity conditions, the weld pool dynamics are dominated by capillary and/or electromagnetic forces (depending on the welding technique employed). Thus, even though gravity-induced convection and sedimentation are absent, Marangoni-induced convection (due to the dependence of surface tension on temperature and composition) may be strong. Additionally, there can be electromagnetic stirring forces in the presence of a welding current. The shape of the weld pool that moves in concert with the welding rod is determined by the interplay among these forces. This interplay is not satisfactorily understood. The weld pool shape in turn affects the weld quality. For example, a cusp shape at the trailing edge produces a seam that is generally detrimental to the materials properties since impurities tend to segregate there.

Since welding involves continuous solidification of the trailing edge of the moving molten zone, gravity level will have some effect on the resulting microstructure. Typical microstructure variables in welded material that are affected are the grain size, distribution of phases, distribution of inclusions, and porosity and cracks.

Direct Manufacturing: An important new technology, direct manufacturing, is being actively developed for making metal, ceramic, or polymer piece parts by computer-controlled step-by-step deposition rather than by the machining of bulk feedstock. There are many variants of direct manufacturing and they go by a number of names such as rapid prototyping, thermal spray, and free form fabrication. All these systems involve a three-dimensional rendering and the production of a complex physical form by the continuous layer-by-layer buildup of metals, ceramics, or polymers. The subsystems involved are, basically, a powder or delivery system, a mechanical subsystem to drive the building of the part, a heat source, and a control subsystem. The powder delivery subsystem consists of a compressed gas supply, a powder feeder, and a cyclone mixer. The powder is fed through a nozzle where the objects are made. A multi-axis mechanical subsystem is used to manipulate the object under the heat source. A microcomputer control subsystem drives the mechanical stage and the power source.

These computer-controlled layer deposition techniques allow the direct production of high-value replacement parts without the use of conventional casting, forging, and machining. Further, the ability to produce new shapes at will lends itself to rapid, flexible, customized production and offers considerable potential for the extraterrestrial production of spare parts. Though these processes are in their infancy, the potential advantages for in-space fabrication are obvious.

Further technology development and actual implementation of this technology require that considerable research be done in the area of microstructure control. The research is necessary to learn how to control the process to allow tailoring the microstructure of each part manufactured, thus ensuring that the resulting properties are appropriate for the desired application. The melt pools involved in the buildup of the layers contain very large thermal gradients. As a result, both surface-tension-driven flows and gravity-driven flows can be large, leading to significant effects on the microstructure, which must be understood. Also, the powder feed is delivered by forced convection, and the powder particles not captured by incorporation into the process must be recovered for contamination control and/or reuse. Current recovery methods depend on gravitational settling, so alternative methods will be necessary in microgravity.

Fabrication of structural components: Both theoretical and experimental rheological studies are needed to understand the influence of the in-space environment on fabrication processes under microgravity conditions. One process being considered is free-form fabrication, which typically involves the use of a powdered form of a material and a focused heat source to build a desired part or component in a layer by-layer fashion. However, in microgravity, the behavior of powder and molten materials is widely different from their behavior on the ground. Innovative methods (e.g. applied external fields) for controlling materials flow in "free space" fabrication are needed. Many of the processes being considered involve layering concepts. The effects of microgravity on the surface cohesion of materials during deposition, material deposition rates, effective bonding between layers, and required delay time between layers must be characterized to understand the properties and quality of freeform fabricated layered components produced in this environment.

Recent breakthroughs in new materials, such as nanotubes, have opened new doors in how materials' properties can be conceived, managed, and controlled to enable properties never achieved before. Because of the fast heating and cooling associated with free-form fabrication techniques, a new class of hybrid materials with controlled microstructures is possible with new, unique properties. It is also possible to integrate micro (5 μm) and nano (0.2 μm) hairs in the same fabrication process. It is expected that synthetic hairs attachment strength can approach that of geckos. Research in this area might produce new space related materials that might be uniquely suitable for space extreme environmental conditions. The effect of charge mitigation, adsorption, adhesion, surface temperature, and other surface effects during materials deposition are also expected to play a significant role in developing successful in-space fabrication techniques.

Fabrication of complex structures will ultimately require assembly of multiple components. Therefore, modeling and experimental studies of subtractive (e.g., cutting and ablation), additive (e.g., melting), and adhesive methods for manufacturing structures and parts in space are required.

There is a need to evaluate and potentially develop various materials fabrication tools, machines, and techniques such as selective laser sintering, fused deposition modeling (FDM), laminated objects manufacturing, sterolithography, multi-jet modeling, 3D printing, electron beam welding (EBW), ultrasonic object consolidation (UOC), laser engineered net shaping LENS), etc. Machines have been built that can produce parts under microgravity conditions, but the need is to develop processes and machines which can use microgravity as an asset as they produce parts.

Fabrication of Solar Sail Systems: Advanced materials requirements for propulsion concepts are described in Section IV, Materials Science for Advanced Space Propulsion. In addition to the development of new materials for the sails, materials research is required for solar sail systems that are capable of being produced, self-deployed, or assembled in-space.

Predictive Modeling, Reliability and Risk Assessment

Integral to the successful integration and use in space of improved understanding of materials phenomena, processes, and technology developments is the development of commensurate development of mathematical simulations and predictive models.

It is clear that it will not be possible to arrive at confident design conclusions through a costly and time consuming process of repeated tests in space of the many important systems and components. Rather, the approach should be to develop physically based computational models that are then fully assessed against relevant microgravity data. These models could then be used to optimize design and to direct and support the scale-up of those space experiments used to evaluate subsystems that cannot be tested at full scale in space. Such models will quantitatively characterize the fundamental phenomena and processes of greatest significance and lead to the necessary technology developments for in-space fabrication. In addition, they would also provide a necessary foundation for establishing desired reliability and safety levels. Further, process simulation and predictive modeling will be beneficial for designing advanced materials and fabrication processes in a cost effective manner. Research in this area is expected to include modeling of fluid flow, heat transfer, and microstructure development, evolution, and control as influenced by materials processing methods.

System reliability is crucial. To address reliability with appropriate rigor and completeness, probabilistic risk assessment (PRA) or probabilistic failure analysis (PFA) techniques would be very beneficial. PRA/PFA is a proven methodology that has been widely and successfully used. It employs fault and event analysis to determine the relative likelihood of the failure modes of specific designs. While it can be used to identify weaknesses in designs and components and can therefore be used to promote design reliability, simplicity, redundancy, and maintainability, it could also potentially be coupled with appropriate real-time sensor detection of critical parameters to allow effective diagnostic and prognostic evaluation, thus allowing critical components to be fabricated and replaced in space prior to failure or unacceptable degradation.

Modeling of propellant and materials production from lunar regolith (metals, O_2) and polar ice (H_2O, H_2, O_2), Mars regolith, Phobos (or carbonaceous asteroid) regolith, structural modeling of alkali borate melts, and modeling of sulfide capacities in silicate melts are a few examples of the modeling of materials under microgravity that are needed.

In-space Repair of Structural Components

The complexity and duration of future missions increases the need for repair capabilities. Also, the initiation of human missions beyond low Earth orbit will depend on NASA being able to demonstrate that the astronauts will be safe by providing the ability to replace or repair failed or underperforming components, especially for long distance and duration missions. The goal of this technology development effort is to provide basic essential repair capabilities through joining, bonding, adhesives, welding, soldering, riveting and fasteners.

Materials design is key to achieve repair functions. The repair function starts from the selection of materials, the type and amounts of needed impurities (e.g. alloying agents), and its microstructure, which determines its physical and mechanical characteristics. A better understanding and documentation of low-gravity materials property data is needed as a function of both processing and fabrication processes. As an example, ionic liquids have applications in transition metal catalysis, batteries, capacitors, metal deposition and heat transfer and energy storage. The ideal property of a material for repair is that it can change its properties by changing its composition or constituents. The properties of ionic liquids can be tailored by changing the anion/cation ratio. It would be useful to have a selection of materials whereby a range of properties can be achieved by varying a limited number of parameters during processing. A range of properties are needed that can be adapted to various repair missions. Ionic liquids can also be used for Aluminum and other metal extractions. The viscosity of aluminum can be changed by adding SiC as a controlled impurity. Similar phenomena of on demand characteristics change is an essential technology development that must be achieved if in space repair is to become a reality. Dry adhesive type material including tape, ad-hoc Velcro, that works on any surface (Robotics, EVA or IVA) in vacuum and microgravity. These materials need to adhere to any surface with rapid attachment and detachment while eliminating the need for mating surfaces and pre-scarring. Temporary attachment using adhesive patches are also needed which could lead, if necessary, to permanent connections, that could be made in the future without need for additional equipment or procedures (i.e. truss assembly).

IV. Materials Science for Advanced Space Propulsion

Electric propulsion includes any plasma propulsion device that derives its energy from electrical sources. The momentum change induced and the resulting propulsive accelerations may arise from various electrothermal, electrostatic, or electromagnetic mechanisms. Applications include orbit transfer, maneuvering, maintenance, and disposal in low earth orbit, planetary space, and on interstellar platforms. Materials are needed that do not experience significant degradation in properties during long duration (up to 20 years) exposure to hostile environments including high temperatures and intense space radiation. These include materials for the following applications: high voltage insulation; electronic components; high strength conventional magnets; high transition temperature, critical field and mechanical strength super-conducting magnets; high efficiency solar cells; light weight and high voltage capacitors, easily obtainable, easily ionizable, non-contaminating fuels, and long-life discharge initiation electrodes. In addition, data are needed for sputter yield during low energy sputtering.

Nuclear Electric Propulsion is based on the concept of converting thermal energy from a fission reactor to electrical energy in order to drive an electric thruster. Power conversion for unmanned missions can be done using the Brayton- or Stirling- cycle engines, or by thermoelectric converters. For manned missions or other missions with a much greater power demand, the Brayton- or Rankine-cycle will be needed. Total energy requirements for scientific deep-space applications is 25-250KW_e, while for manned exploration missions, the power levels needed can range from 2-30 MW_e.

These and other **Advanced Propulsion Research** concepts have the following primary research needs in common:

Electrodes and Grids Magnetohydrodynamic (MHD) systems are of interest to support missions that require a lifetime of 12 years. Current systems have grids with lifetimes on the order of hours, with a surface area of 1-2 m^2. Systems need to be able to survive high temperatures, high current flow (10kA), and severe radiation environments. Improvements in materials for electrode design could improve performance and lifetime.

Efficient *dissipation of excess heat* is the single most critical issue for in-space propulsion systems. Operation of systems at higher temperature increases efficiency, and will also improve radiation properties. Thus, the area of the radiation systems can be reduced. The limitations are on the materials, and in particular on their high temperature mechanical properties and their emissivities. The need to withstand the operating environment of radiation and micrometeoroid debris are also critical aspects of a thermal management system.

Advancements in *radiators and heat pipes* are crucial to dissipate heat generated from in-space propulsion systems. The efficiencies of power conversion cycles vary linearly with the cycle rejection temperature. In general, the lower the rejection temperature the higher the efficiency. However, for in-space applications, the size and mass of the radiators increases according to the fourth power of the cycle rejection temperature. Therefore, the combined mass of a specific power conversion system and the radiator will have a minimum mass at a specific radiator temperature. In general a higher heat rejection temperature results in a lower radiator mass and overall system mass.

At least a 25% improvement in radiators is needed for a minimum operating temperature of 1200K. Other systems may encounter operating environments as high as 2000K with a goal of cooling Xe/He to < 500K. Sodium, and lithium for higher temperatures, are under consideration as working fluids. Future radiator systems require lightweight, high thermal conductivity, high-temperature materials that are resistant to corrosion and micrometeoroid impacts; self-healing materials for this application are of interest. Deployable radiators are desired with a target emissivity coating >0.9, an areal density of 2-6 kg/m^2, an area of less than 1500 m^2, and able to function in a high radiation environment. Current concepts stipulate 300 m length of deployable radiator, with aluminum the material of choice.

Research Areas:

- To what extent can multi-layer thin wall tubing, with or without an interior coating, be developed to save mass as radiator components and maximize thermal efficiency? This can include research on the substrate, coating, and their dimensions and properties in order to obtain the desired performance from the system.
- Which long-life, high strength, high temperature concepts in materials design can be applied to improve efficiency and raise the operating temperatures of heat pipes?
- How can materials be synthesized and processed to increase emissivity and maintain their properties in the environment of high radiation, including micrometeoroid and other strikes?
- How can one optimize the operation of heat pipes in low gravity by means of thermal and fluid computational simulations of heat pipe performance with candidate materials? What is the sensitivity of heat pipe performance to the availability of accurate thermophysical property data such as thermal and mass diffusivity, viscosity, and the wetting characteristics of candidate materials; what steps should be taken to ascertain these unknown properties?

Lightweight magnets are absolutely enabling to a wide range of advanced propulsion systems, including plasma thrusters, fusion propulsion, electric thrusters, and magneto-hydrodynamic (MHD) accelerators. In the long term, they are even required for anti-matter containment in systems that will utilize nuclear particle physics principles. The challenge is to achieve low weight, large volume, high field magnets, and requisite improvements in the strength of associated structural support materials. Common magnet systems have specific energies ($E_{sp} = \frac{B^2}{2\mu} \times \frac{V}{m}$) on the order of 5 kilojoules per kilogram where B is the magnetic flux density, V is the enclosed working volume, μ is the magnetic permeability and m is the mass. The specific energy requirements for many advanced propulsion systems is up to 1,000 kJ/kg. In order to achieve the desired specific energy, materials are needed to make lightweight confinement structures capable of withstanding the enormous Lorentz force exerted by the magnet.

One of the primary considerations for superconducting magnet system design is the total weight of the system, which includes the magnet, the cryogenic container, the cryogenics, and the electrical power supply to energize the magnet. In addition, while it would be desirable to operate a superconducting magnet in the persistent current mode so that no power would have to be supplied once it is energized, this situation may not be practical or realistic. Because the field produced by the magnet may be used for plasma confinement, there will be both steady and transient fields acting on the coil causing field changes and possible quenching of the superconducting material. An excess of 100 amps will be required to fully energize the coil and a standard DC supply is too heavy for this application. With zero resistance joints, a lightweight superconducting flux-pump could be used to energize the magnet. This type of supply can be operated from low voltage, low current power supplies with a feedback system that will correct the field produced by the coil.

Research Areas:

- By use of novel techniques, what materials can be produced for permanent magnets that will be lightweight, have high field strength, and operate at high temperatures?
- How can superconducting zero resistance electrical connections be achieved in high temperature superconducting wires? Can low-density, high-strength forms be developed on which to wind the coils?
- How can recent developments in ultra-conductors (such as high purity aluminum or carbon nano-tubes) be utilized to produce very high field strength and very light weight magnets?
- How can materials provide lightweight shielding of the coils against pulsed magnetic fields during plasma containment, against high temperatures generated in plasmas, and against nuclear radiation damage from reactions in the plasma?

Just as with the previous propulsion technologies, materials to be used for **Advanced Chemical Propulsion** concepts must be improved to ensure robust health and durability of spacecraft in extreme environments over extended periods of time. Optimum propellant tank pressures, chamber operating pressures and temperatures depend on the propellant. However, future requirements for system-level health will include the capacity of system components to resist wear and degradation from radiation, low temperature, micrometeoroid impact, high engine chamber temperatures due to the use of high performance propellants, high chamber pressures due to pump fed systems, etc.

Research Areas:

- *Multi-layered coatings* offer a means for achieving the materials properties required for advanced propulsion systems. Such coatings may consist of metals, ceramics, or polymers (silicon or carbon-based). For example, advancements in refractory ceramic coatings used on the refractory metal combustion chambers could extend the operating chamber temperature range above 3000°C. Also, it is necessary that improvements be made in methods for processing multi-layered materials. These include: atomic layer deposition (ALD), chemical vapor deposition (CVD), and chemical vapor infiltration (CVI), to name a few. Important areas of study include: the effects of layer thickness, composition, and control of defect content on thermal, chemical, and mechanical properties; how to improve coverage over complex geometries; thermal, chemical, and mechanical compatibility at interfaces; phase stability at high temperatures and during thermal cycling; and materials response to space-based environmental exposure.
- *Sensors* are needed that can enable active control of fuel mixture ratios in combustion engines using feedback loops. These sensors must be capable of surviving hostile environments over 10-15 years of operation. Specific measurements include the concentration (fraction) of the various combustion products in the plume.
- Materials are needed to enable the development of *linerless pressurant tanks* with a mission life of 15 years with an integrated structural/micrometeoroid/thermal protection subsystem. It is advantageous to remove inert gas tank metal liners and still maintain the purity of the contained inert gas (GN2, GHe, autogenous GO2, autogenous GH2, gaseous and liquid Xe, Kr) at high pressure (up to 10,000 psia). These linerless tanks will reduce tank mass, decrease system complexity and decrease tank fabrication costs for future spacecraft systems.

Aerocapture relies on aerodynamic drag with an atmosphere to achieve orbit capture. Aerodynamic drag can be accomplished by means of rigid aeroshells or by inflatable structures called ballutes (balloon/parachutes). Protection from aerodynamic heating requires careful trajectory selection, a Thermal Protection System (TPS), and monitoring by sensors. The leading surfaces of rigid aeroshell systems can be protected by ablation, or by use of high-temperature-resistant, non-ablative materials that offer sufficient insulating ability to protect payloads. Ballutes require materials capable of being stored compactly and deployed reliably in space. Areas that could benefit from research include lightweight rigid aeroshell materials, advanced bonding agents, thin film ballute materials, and sensors that monitor conditions of the aerocapture system (either rigid aeroshell or ballute).

Research Areas:

- **Rigid Aeroshells:**
  Leading Edge Materials experience the brunt of the aerodynamic heating and are mission dependent. Current designs integrate leading edge materials into a thermal protection system (TPS) which is a layered system of metallic honeycomb sandwich and insulation (densities of 224 kg/m^3, or 14 lbs/ft^3, with areal densities ranging from 10-26 kg/m^2) and are limited to a heat flux of 700 W/cm^2. Analyses of missions to date identify the following requirements: (1) high temperature operation > 1925°C, (2) high strength (modulus in tens of GPa), (3) high reflectivity in UV, (4) high emissivity in VIS/IR, >

0.9, (5) low mass (less than that of typical carbon composites. Insulation requirements include a suite of materials to span high temperature operation to maximum > 1750°C. Improvements needed in leading edge materials include having highly anisotropic thermal properties, i.e. high thermal diffusivity tangential to the spacecraft shape and low thermal diffusivity normal to the spacecraft shape. The materials need high strength (modulus in tens of GPa) and very low density (tens of kg/m^3. Incorporation of aerogel-based materials in the overall thermal protection system is of interest. We are not soliciting the development of thermal protection systems. We are soliciting for the development of materials and/or processes that will enable new leading edge materials that would subsequently be used in a new, higher performance TPS.
Bonding Agents must be compatible with materials being bonded over the full range of temperature. It would be highly beneficial to have bonding agents or bonding processes that create bonds that can operate in excess of 250°C.
Sensors will need to be embedded in the appropriate rigid aeroshell materials, reliably measure temperatures from ~1500° – 1700°C, and sustain stresses consistent with launch and re-entry. This could involve sensors fabricated as components within the materials (i.e. smart materials).

- **Ballutes:**
  Materials used to fabricate ballutes must retain required properties if compacted (creased) for long periods (10 years), cold-soaked, exposed to particulate and radiation damage and also when deployed and exposed to very high temperatures and appreciable stresses. Inflation by low-density gases (He, Ne, H_2, etc.) is the current means of deployment and the thin containment walls must be impermeable to these gases, which are being heated within. The ability to nondestructively test and ensure the absence of degradation from phase transitions, moisture and other common environmental exposures is required. A particular interest has been expressed in aerogel-based, or similar, coatings that might enhance materials performance.

Solar sails use the momentum transfer from reflected light to provide a propulsion force. The sun deposits approximately 9 Newtons per square kilometer at 1 AU. The low mass sail requires ultra-thin materials (micron to submicron thickness) with reflective coatings that must be tear and wrinkle resistant, deployable, and, because of the close approach to the sun, requires surviving severe thermal (500°C at 0.1 AU) radiation (ultraviolet + low energy charged particles <100 KeV), and micrometeoroid environments over a mission life of 10-15 years within 0.1 AU. Ultimate goals are to survive the extremely hostile thermal environment (2000°C) and cosmic radiation flux at 3 solar radii. Sail surfaces facing toward the sun need coatings with a reflectivity of 0.99 and surfaces facing away from the sun need emissivity ranging from 0.9 to 0.99.

A mast and a perpendicular control boom support the sail material. Support booms/masts must be deployable from payload package. The near term goal is 12-15 g/m^2 areal density (including support structure but not including boom, science package & bus). The long-term goal for an interstellar probe (417 meter hexagon) is an areal density of 1 to 0.5 g/m^2 (including support structure) for the 90,000 m^2 sail. The key requirement is to reduce mass of boom design while maintaining rigidity/structural integrity.

<u>*Materials to endure the space environment*</u>, such as radiation resistant materials with high emissivity and reflectivity over the range of temperature (up to 500° C) are required. For near-term designs, the reflectivity might be sacrificed for radiation exposure resistance, higher temperature capability, and high emissivity. Alternatively, a very high reflectivity, radiation hard sail material with current state of the art emissivity might be suitable.

Research Areas:

- How can we develop a higher temperature and radiation resistant polymeric material which might include highly cross-linked thermoset composites rigidized after deployment by thermal curing, UV curing, etc.
- How will meteoroid/orbital debris impacts affect the materials and the overall structure? Concepts that might also include self-healing materials would be of interest.
- Increasing the reflectivity achieves two important advantages. The efficiency of the sail increases and the amount of absorbed energy converted to heat decreases. How can the ideal reflectivity (0.99) be approached using nanoscale dielectric multiplayer photonic band gap materials?
- What effects will UV and charged particle radiation have on the mechanical strength as well as the thermo-optical properties of the materials?
- How might surface morphological texturing be used to achieve higher emissivity of the surface?
- How can aerogel beams be fabricated in-situ for structural supports?
- What are the materials implications of using inflatable structure concepts for solar sails?

<u>*Sensors*</u> will need to be embedded in the appropriate materials and locations to provide for the collection of sufficient data to assess the performance of the solar sail in the space environment. Key stresses and forces in the sail structure and sail film as well as temperatures must be measured. The sensors should be easily accommodated in the solar sail structure to reduce the impact of such instrumentation on system resources, integration, and solar sail deployment. Smart materials and self-healing concepts should be explored.

A tether for a **MXER** (Momentum-eXchange/Electrodynamic Reboost) tether facility would embody both high-strength polymeric materials and electrically conductive elements. Significant advances in materials science are required for this system to mature into a useable technology for propulsion in and beyond low Earth orbit. Several materials (such as highly-oriented polyethylene, PBO, and PIPD) have sufficient specific tensile strength to build attractive MXER tether systems, but no one material currently embodies the resistance to atomic oxygen (AO) and ultraviolet light (UV) that are required for long-duration orbital operations. Additionally, electrically conductive tether elements are necessary for electrodynamic reboost. Lightweight conductors such as aluminum might be bound within the polymer or co-wound with the polymer fiber. Another promising technique might be to make the polymer itself conductive. Several of the candidate polymer materials (PBO and PIPD) possess the pi-conjugated structure (alternating single-double carbon bonds) of electrically conductive polymers, and one (PBO) has been made conductive experimentally. Conductivity on the same order of aluminum would be required to replace metallic conductors with conductive polymers. Ease of manufacturing, testing, fabrication, winding, and deployment of materials developed are also important factors to be considered.

Research Areas:

- How can a coating or a copolymer for tethers provide protection against atomic oxygen and UV without adding excessive mass?
- Can a metallic conductor be embedded in the high-strength polymer with a minimal impact to the polymer's load-bearing capability?
- Can a high-strength polymer be made to have significant electrical conductivity (e.g. through doping or other mechanisms)? Alternatively, can a highly-conductive polymer be co-polymerized with a high-strength polymer? Is it stable in the operational environment? How would this affect strength, electrical conductivity, and other properties?